Helsinki Center of Economic Research

Discussion Papers

Air Pollution in Europe 2020: The Gravity Model and EKC Decomposition

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Discussion Paper No. 292
April 2010

ISSN 1795-0562

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HECER
Discussion Paper No. 292

Environmental Mortality and Long-Run Growth*

Abstract

This paper discusses air pollution in Europe by developing a gravity model for transboundary emissions, while the EKC decomposition is utilized to calculate the association between emissions and income. Since the income elasticity of air pollution turns out to be negative, the considerable income increase predicted here by estimating their income trends until 2020 will induce a marked decrease in emissions in many countries. Nevertheless, because total deposits, through emission import and export, depend on emissions in the area as a whole, emission decreases in individual countries will be annulled unless there is a concomitant emission decrease in Europe.

JEL Classification: Q01, Q53, Q54, J11

Keywords: transboundary air pollution, gravity model, environmental Kuznets curve, Europe.

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* The authors are grateful to Adriaan Perrels, Marke Hongisto, Tuija Ruoho-Airola, Ari Venäläinen, Olli Ropponen, Marko Tainio, Heikki Pursiainen, Essi Eerola, and Katariina Nilsson-Hakkala for their helpful comments.

1 Introduction

In spite of some promising news, air pollution is still a serious environmental problem in Europe with a high social cost, incorporating primarily public health, both lethal (mortality) and sub-lethal (morbidity) effects. Even in areas with relatively low levels of pollution, public health effects can be substantial, since they can occur at low concentrations and a large number of people can potentially breathe in such pollutants. In Europe, it has been calculated by WHO that the annual loss of lives is still approximately 350 000. Besides public health, air pollution impacts the climate as the particles scatter and absorb solar and infrared radiation in the atmosphere, changing the Earth's albedo.

Two questions need special attention. The first is the dependence of countries on emissions produced by their neighbors as transboundary emissions. Second, given that air pollution is mainly generated by economic activity, there is a concern over how much emissions are going to grow along with the future economic growth. This paper tries to address both questions.

Our first building block is the gravity model, known to economists from the theory of international trade (McGallum 1995, Helliwel 1998, Harrigan 2003) and here applied to understand the "trade" of emissions between countries. As in the theory of international trade, the gravity approach serves here as a practical solution for calculating trade flows. To summarize the salient features of multilateral emissions trade, we develop a gravity index which indicates how vulnerable a country is to emissions from abroad. This index is then applied to calculate air pollution export, import, and total deposits in the 25 members of the European Union.

The second building block is based on the Environmental Kuznets Curve (*EKC*) which suggests that pollution depends on competing effects, namely, technology-composition and scale effects, the total effect of which dictates the response of pollution to economic growth (Arrow et al. 1995, Grossman and Krueger 1995). This paper utilizes this decomposition, which allows one to concentrate on individual effects rather than their complex combination. Since in the European data the income elasticity of air pollution turns out to be negative, the considerable income increase predicted here by estimating the income trends up to 2020 indicates that there should be a marked decrease in emissions in many countries. Nevertheless, because a total deposit, through emission import and export, depends on emissions of the area as a whole, emission decreases in individual countries will be nullified unless there is a concomitant emission decrease in Europe.

The paper is organized as follows: Section 2 introduces main ideas of the gravity model and Section 3 gives several details and applies this model to derive transboundary air pollution in the 25 members of the European Union. Section 4 projects air pollution in 2020 by applying the *EKC* decomposition to estimate the association between emissions and incomes, and by estimating incomes in 2020. Section 5 provides the sensitivity analysis and Section 6 discusses the findings and closes the paper.

2 The gravity model for transboundary air pollution.

Meteorologists have applied several methods of evaluating transboundary air pollution. The so-called receptor method aims to discover the sources of pollution observed in the field data by calculating the appropriate upwind trajectories (e.g., Niemi et al. 2009), while the dispersion method calculates the downwind trajectories to determine the destination of emissions from spesified sources. A complete ($m \times n$) receptor-source matrix reports all m sources and n receptors of emissions. It is also possible to calculate intake fractions showing the ratio of pollution from other than local sources (Greco et al. 2007, Tainio et al. 2009). Some methods, such as the Gaussian plume model of aerosol dispersion are based on a well-developed theory

(Nigge 2001), whereas some others derive from statistical and simulation techniques (Moussiopoulos et al. 2004, Borge et al. 2007). For a survey, see Scheringer (2009).

This paper proposes that transboundary air pollution can be understood by applying the concept of gravity.[1] The original gravity equation

$$G_{1,2} = \gamma \frac{M_1 M_2}{{d_{1,2}}^2}$$

suggests that the gravity between two objects is determined by masses M_1 and M_1 and distance $d_{1,2}$ between them, while γ is the gravity constant. The gravity equation has been intensively utilized in the theory of international trade that claims that bilateral trade depends on both the gross domestic product (GDP) and the geographical distance between partners (McCallum 1995, Helliwell 1998, Harrigan 2003). In this paper, we propose that the "trade" of emissions should obey

$$IM_{1,2} = \gamma \frac{E_1 E_2}{{d_{1,2}}^2}, \tag{1}$$

where $IM_{1,2}$ refers to the net import of emissions from country 2 to country 1 and E_1 and E_2 refer to their emissions. Other elements to dictate net import, namely, the dominant wind directions and geographical areas, are collected into the constant γ.

Trade, however, is seldom bilateral. Like goods, emissions are traded with several partners, even from far-distant locations. Therefore, "[t]he trick is to find a parsimonious way of summarizing the salient aspects..." of multilateral trade (Helliwell 1997). Hence, the bilateral expression $E_1 E_2 / {d_{1,2}}^2$ should be replaced by its multilateral counterpart, known as the index of centrality in the trade theory. For country i, this index is given by

$$Centrality_i = \sum_{j=1}^{n} \frac{E_j}{{d_{i,j}}^2}, \tag{2}$$

[1] The principal elements are discussed in this section, whereas the next section gives the application details.

where $E_j/{d_{i,j}}^2 = 0$ if $j = i$.[2]

To construct the multilateral counterpart of the constant γ, consider the role of the dominant wind directions. Since countries which receive winds from several countries in the trading area are most prone to receive emissions, we construct a downwind index, the element of which $(w_{i,j})$ gives the probability of wind in country i from country j. Aggregating among countries, the downwind index for country i becomes

$$Downwind_i = \sum_{j=1}^{n} w_{i,j}. \tag{3}$$

Finally, because large countries tend to capture the major proportion of emissions, we calculate an area index

$$Area_i = \frac{A_i}{\sum\limits_{j=1}^{n} A_j}, \tag{4}$$

where A_i is the area of country i. Note that for a given country, the downwind and area indexes are constant, whereas centrality varies along with emissions.[3]

Taken together, centrality, downwind and area indexes indicate the vulnerability of a country to emissions from abroad:

$$Gravity_i = \frac{Downvind_i \times Area_i \times Centrality_i}{\sum\limits_{i=1}^{n} Downwind_i \times Area_i \times Centrality_i}. \tag{5}$$

Thus, $Gravity_i$ is an (unweighted) combined index, implying that the largest emission "imports" take place in big, central, downwind countries.

[2]For the role of centrality in the trade theory, see Harrigan 2003. Alternatively, one can use concept of remoteness, which is the inverse of (2) (Helliwell 1997).

[3]The wind direction has its trade theory counterpart in the trade costs as it is more "expensive" to trade upwind than downwind. The counterpart of area in the trade theory is the scale effect.

3 Application to Europe

As an application of the gravity model above, we calculate outdoor air pollution trade for the 25 members of the European Union (EU_{25}). Air pollution consists of several pollutants, such as ozone, nitrogen dioxide, particulate matter, and so on. Since particulate matter, PM, is closely associated with other air pollutants, WHO suggests that it should be used as an *indicator* of outdoor air pollution (Cohen et al. 2004). Particulate matter consists of solid particles of varying size and chemical composition, mainly generated by energy combustion, which is classified according to its maximum diameter size, the main groups being $PM_{2.5}$ and PM_{10}. In this paper, we concentrate on $PM_{2.5}$. We use the data which is available from Amann et al. (2007) who report $PM_{2.5}$ emissions for EU_{25} for the year 2000.

We utilize several helpful simplifications, the first comes again from the gravity theory, which assumes that all masses are concentrated in gravity centers. Analogously, we assume that the geographical area of country i is a circle with radius r_i with all emission activities concentrated at its midpoint. To dictate what fraction of emissions is "consumed" at home and which fraction is "exported", we thus need information about the maximal extension of $PM_{2.5}$ emissions. Greco et al. (2007) have found that in a sample of 3080 U.S. counties, 90% of $PM_{2.5}$ emissions stay within a distance of 950 km, while Borge et al. (2007) suggest that some emission may even migrate from the U.S. to Europe. For our purposes, the most suitable estimate is given by Tainio et al. (2009), who derive the $Intake\ fraction(\%) = 25.68 + 0.00008\pi r^2$ from a sample of 38 European countries, implying that practically all emissions stay within a radius of $\bar{r} = 550$ km from their source. Thus, given radius r_i for country i, this rule can be used to calculate the domestic consumption and export which are reported in Table 1 after emissions and the values for r_i. The last row of Table 1 aggregates over countries, indicating that, of the total emissions of 1579.79 kilotons, 832.28 kilotons (52.68%) are consumed domestically, whereas 747.51 kilotons (47.32%) are exported.

The second part of Table 1 concentrates on the import of emissions as suggested by the gravity model above. To calculate the Centrality index

$$Centrality_i = \sum_{j=1}^{n} \frac{E_j}{{d_{i,j}}^2}$$

we assume $E_j/{d_{i,j}}^2 = 0$ for $d_{i,j} > 550$, i.e., we only accept countries which are close enough to send $PM_{2.5}$ emissions to country i. As in the trade theory, we measure the distances between countries as the distances between their capital cities. The values of the centrality index in Table 1 show that Belgium, Luxembourg, The Netherlands, and the Slovak Republic are the most central countries, while neither Cyprus, Greece, nor Malta have (close enough) neighbors in EU_{25}.

To construct the downwind index, we use the wind probabilities (wind map) reported at meteorological sites for capital city airports (WindFinder.com 2009). The average annual wind probabilities are aggregated over the quarters (north-east, south-east, south-west, north-west) for each country. The element $w_{i,j}$ thus gives the probability of wind from a quarter which includes the capital city of country j, this quarter being defined by the capital city of country i. If the distance between the capital cities exceeds $550\,km$, then $w_{i,j} = 0$. Column 6 in Table 1 shows that while Cyprus, Greece, and Malta receive no winds and the most western and southern countries, such as Ireland, Italy, Portugal, and Spain receive only some, the eastern countries, such as the Czech Republic, Austria, and Hungary receive winds from several sources. Finally, column 7 in Table 1 shows the values for the area index for each country.

The final step is to combine the gravity index with the emissions export data. For simplicity, we assume that EU_{25} is a closed emission-trading area and its net trade with other partners is zero.[4] All the emissions exported

[4]The most important partners are Russia, Belarus, and Turkey, all of which are heavy

EU_{25}	1 Emission ktn	2 Radius km	3 Domest. ktn	4 Export ktn	5 Centrality index	6 Downwind index	7 Area index	8 Import ktn	9 Total ktn
Austria	28.18	163.39	9.13	19.05	1.02	1.45	0.021	49.87	59.00
Belgium	32.86	98.58	9.24	23.62	1.77	1.00	0.007	21.63	30.87
Cyprus	2.18	54.26	0.58	1.60	0.00	0.00	0.002	0.00	0.58
Czech Rep.	42.69	158.44	13.66	29.03	1.22	1.35	0.019	52.10	65.75
Denmark	25.97	117.12	7.56	18.41	0.50	0.42	0.011	3.59	11.15
Estonia	21.69	119.98	6.35	15.34	0.47	1.00	0.011	8.54	14.89
Finland	28.26	328.08	14.90	13.36	0.36	0.86	0.083	41.61	56.51
France	328.23	453.26	253.76	74.47	0.52	0.99	0.159	132.35	386.11
Germany	159.86	337.11	86.71	73.15	0.67	0.94	0.088	90.53	177.24
Greece	47.32	204.93	17.15	30.17	0.00	0.00	0.032	0.00	17.15
Hungary	52.38	172.08	17.35	35.03	0.72	1.49	0.023	39.99	57.34
Ireland	14.16	149.57	4.43	9.73	0.24	0.23	0.017	1.52	5.95
Italy	150.27	309.65	74.80	75.47	0.02	0.26	0.074	0.77	75.57
Latvia	10.93	143.39	3.37	7.56	0.26	0.85	0.016	5.75	9.12
Lithuania	12.5	141.05	3.83	8.67	0.60	0.94	0.015	14.06	17.90
Luxemb.	2.73	0.91	0.70	2.03	1.63	0.96	0.000	0.00	0.70
Malta	0.59	10.03	0.15	0.44	0.00	0.00	0.000	0.00	0.15
Netherl.	26.78	114.97	7.77	19.01	1.27	1.24	0.010	26.26	34.02
Poland	202.7	315.48	102.76	99.94	0.55	1.18	0.077	80.72	183.48
Portugal	76.99	171.49	25.46	51.53	0.30	0.31	0.023	3.48	28.94
Slovak Rep.	14.5	124.69	4.29	10.21	1.25	0.64	0.012	15.72	20.01
Slovenia	12.08	80.33	3.30	8.78	0.69	1.09	0.005	6.09	9.39
Spain	151.14	400.85	99.85	51.29	0.15	0.39	0.124	12.17	112.01
Sweden	25.4	378.45	15.67	9.73	0.20	1.03	0.111	37.77	53.44
United Kgd.	109.4	279.16	49.52	59.88	1.17	0.90	0.060	102.99	152.51
Sum	1579.79		832.28	747.51				747.51	1579.79

Table 1: Emissions, exports, imports, and total deposits in 2000.

from EU_{25} are $\sum_{j=1}^{25} EX_j$ (747.51 kilotons, Table 1). The crucial simplifying trick is that since the gravity index takes care of the imports of individual countries, we can simply distribute the total bulk of exports to countries according to this index to get

$$IM_i = \sum_{j=1}^{25} EX_j \times Gravity_i, \tag{6}$$

where IM_i is the import of emissions in country i.

Column 8 in Table 1 reports emission imports, and the last column adds imports and domestic consumption to total deposits. To take an example, note that out of its emissions of 28.18 kilotons, Austria consumes 9.13 kilotons domestically and exports 19.05 kilotons. Given that its imports are 49.87 kilotons, its total deposit ends up as 59.00 kilotons, so that Austria, as a relatively central and large downwind country, is a heavy net importer of emissions.

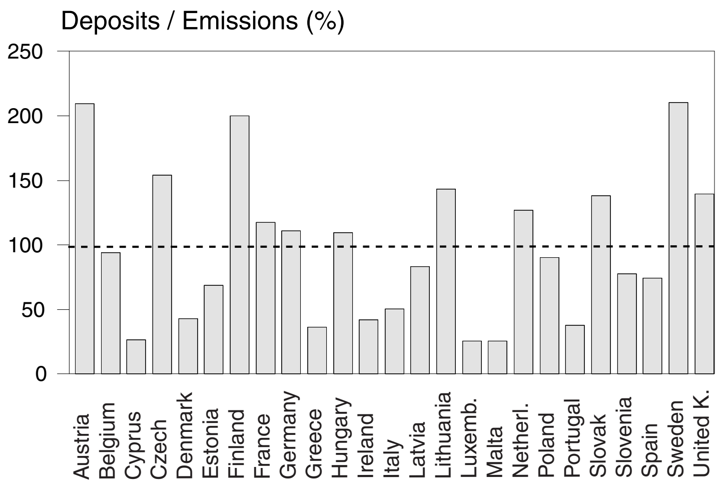

Figure 1: Deposits/Emissions (%).

polluters, but located downwind from EU_{25}. Some pollutants may also arrive in EU_{25} overseas from North America and Africa. Since the data is taken from the $CAFE$ project of the European Union, they are only available to EU_{25}-countries, also leaving some European countries out of this analysis.

Figure 1 illustrates the results from Table 1 by scaling down the emissions to 100 for each country. Thus the number for Austria is derived from $(59.00/28.18) * 100 = 209.36$ (columns 9 and 1). Figure 1 shows that the countries in EU_{25} seem to constitute four categories. The first category is the smallest countries (Cyprus, Luxemburg, Malta) with a low deposit/emission ratio ($< 30\%$), then comes a group net exporters with deposit/emission ratio of $30 - 80\%$ (Greece, Portugal, Ireland, Denmark, Italy, Estonia, Spain, Slovenia), and the third group has a deposit/emission ratio of $80 - 120\%$ (Latvia, Poland, Belgium, Hungary, Germany, France). Finally, there is a group of heavy net importers, (Netherlands, the Slovak Republic, the United Kingdom, Lithuania, the Czech Republic, Finland, Austria, and Sweden) with a deposit/emission ratio of $> 120\%$. The three heaviest net importers, Finland, Austria, and Sweden, are large countries in the eastern or northern part of Europe, i.e., receiving permanent winds from other countries in EU_{25}, and not even their distant location can spare them from the emissions of their neighbors. These heaviest net importers receive so much that their total deposits are twice their own emissions.

The results of the current paper can be compared to those derived by alternative methods. Niemi et al. (2009), by using several methodologies, such as air quality monitoring, backward air mass trajectories, and chemical analysis of particle samples, found that $50-75\%$ of the $PM_{2.5}$ mass in urban areas in Finland originates from long-range transportation. Karppinen et al. (2004) construct and test a linear regression model and found that the long-range transportation contributes to $64 - 76\%$ of the $PM_{2.5}$ concentration in the urban air in Helsinki (Finland). These results are in line with the estimate of 73.63% derived in this paper. An interesting comparison is that with Tainio et al. (2009) who have derived results for Europe by using the intake fraction approach. For EU_{25}, the correlation between the total deposits from Tainio et al. (2009) and from this paper is as high as 84.83%. However, our estimates are smaller in western countries, Portugal, Italy, and Greece, for example, but larger in eastern countries, such as Lithuania, Slovenia, Sweden, Austria, Finland, and Estonia, implying that our estimates may suffer from a somewhat excessive emphasis on wind. Another possibility is that the wind direction, taken from WindFinder.com (2009) and indicating the low-atmospheric situation alone, should be replaced by winds at higher altitudes, probably with larger relevance to pollution transfers but, unfortunately, such a wind map is not available to the authors yet.

4 Emissions and economic growth

In this section, we evaluate the future emissions. Since the $PM_{2.5}$ emissions are mainly generated from economic activities, such as production, consumption, and transportation, as summarized in the gross national product (GDP), in projecting emissions, the association between incomes and emissions needs to be estimated. Unfortunately, data on $PM_{2.5}$ is available only for a single year (2000), making country-specific time series analysis impossible. Therefore, we turn to the alternative approach and estimate the emission-income association from a cross-section of countries. Given that the GDPs of the EU_{25} members are of different magnitudes, we first integrate the data by utilizing the EKC decomposition.

4.1 The *EKC* decomposition

The Environmental Kuznets Curve (EKC) claims that the impact of economic growth (i.e., the increase in the per capita GDP) on pollution is dictated by two effects. On the one hand, the adoption and implementation of cleaner production techniques and the shift to services tends to decrease the emission intensity of the GDP, but the increase in per capita GDP tends to work in the opposite direction because of higher consumption (Arrow et al. 1995, Grossman and Krueger 1995). These effects are known as technology-composition and scale effects respectively. Since emission intensities can be directly compared between countries, we estimate the technology-composition effect from a cross-section of countries and derive the full expression for country-specific emissions mathematically.[5]

Consider the emission intensity of GDP, defined by $\phi = E/GDP$ with E referring to $PM_{2.5}$ emissions as before.[6] Figure 2 illustrates the values of ϕ as a function of the real GDP per capita ($GDPpc$) in 2000 for EU_{25}, showing that richer countries use cleaner production techniques than poorer countries. Several formulas (hyperbolic, exponential, logarithmic) can capture the association between incomes and emissions, but the highest explanatory power is provided by $\phi = \alpha \cdot GDPpc^{\beta}$. Hence, by taking logs, we fit

$$\ln\ \phi_{i,2000} = \ln\ \alpha + \beta \cdot \ln\ GDPpc_{i,2000} + \varepsilon_{i,2000} \tag{7}$$

by OLS. The derived estimates are $\hat{\alpha} = 56298.77$ and $\hat{\beta} = -1.27$. Formula (7) explains 55% of the cross-sectional variation in ϕ.

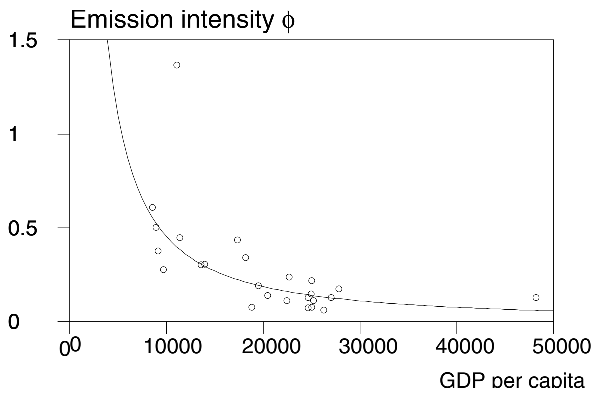

Figure 2: Emission intensity of output ϕ as a function of real GDP per capita ($GDPpc$) in 2000, EU_{25}.

The definition $\phi = E/GDP$ implies $E = \phi \cdot GDP = \phi \cdot GDPpc \cdot L$, where L is population. Applying this to $GDPpc$ and population L in country i at

[5] Testing the Environmental Kuznets Curve *hypothesis* which claims that pollution first increases but then decreases along with economic growth is beyond the scope of the current paper.

[6] The data for $GDPpc$ comes from Heston et al. (2006).

time t, one can derive the country-specific emission functions

$$E_{i,t} = l_i \cdot 56298.77 \cdot GDPpc_{i,t}^{-0.27} \cdot L_{i,t}, \tag{8}$$

where the multiplicative fixed factor l_i is the residual from (7) divided by $\phi_{i,2000}$. Equation (8) shows that the elasticity of emissions with respect to the $GDPpc$ (L) is a negative (positive) constant. Thus, in spite of decreasing emission intensities, the emissions themselves may increase or decrease over time, depending upon the growth rates of $GDPpc$ and L.[7]

4.2 Income, population, and emissions

To provide country-specific projections for emissions in 2020 from (8) we estimate the values for $GDPpc_{i,2020}$ from the time series of $GDPpc_{i,1950-2003}$ by applying linear trends, with country-specific breaks being allowed for the 1973-1982 and 1990-1992 periods. The former break counts the oil crises and the latter the collapse of the Soviet Union. Column 1 in Table 2 shows the projected values for $GDPpc$, column 2 reports R^2 and column 3 provides the implied growth rate of $GDPpc$, which is 2.55% on average for EU_{25}. For $L_{i,2020}$ we utilize the medium variant projection from the United Nations (2007) (column 4), and the implied population growth rates are shown in column 5. Column 6 shows the emissions in 2020 calculated from equation (8).

Repeating the procedure in Section 3, one can now calculate the exported and imported emissions in 2020. Note that the centrality index needs to be updated for emissions in 2020, but the downwind and area indices remain constant. Ultimately, one can calculate the total deposits in 2020 shown in column 7 of Table 2 and indicating that total emissions in EU_{25} will decrease from 1579.79 to 1468.22 kilotons.

[7] Note that (7) (and (8) as derived from (7)) pays no attention to new abatement policies or to innovations in decreasing emissions. In this sense, it can be thought of as a minimum variant for emission decreases in the future.

EU_{25}	1 GDPpc $	2 R^2	3 Growth %	4 POP thousand	5 POP growth %	6 Emissions ktn	7 Deposits ktn
Austria	40220.3	1	1.99	8575.29	0.29	26.77	52.90
Belgium	35445.46	1	1.81	10684.12	0.18	30.86	30.37
Cyprus	56140.91	0.99	5.05	975.21	1.26	2.13	0.56
Czech Re.	18304.08	0.7	1.48	10042.94	-0.11	38.51	57.93
Denmark	37449.54	0.99	1.48	5543.82	0.19	24.86	10.62
Estonia	19721.31	0.53	2.88	1277.64	-0.57	16.54	12.90
Finland	30990.49	0.99	1.55	5433.57	0.24	27.26	48.06
France	35026.15	1	1.68	64824.74	0.45	327.49	382.87
Germany	31851.92	1	1.2	81160.69	-0.07	147.57	156.84
Greece	17441.96	0.99	1.11	11274.29	0.13	45.76	16.58
Hungary	19983.82	0.98	2.81	9620.66	-0.3	42.25	48.02
Ireland	47288.03	0.99	3.2	5055.46	1.43	15.81	6.45
Italy	33390.83	1	1.98	58600.98	0.08	136.95	68.84
Latvia	23234.71	0.96	4.74	2133.68	-0.6	7.48	7.32
Lithuania	23409	0.93	4.69	3187.83	-0.64	8.52	13.56
Luxemb.	93296.29	1	3.3	538.28	1.06	2.82	0.73
Malta	47439.06	1	4.61	426.48	0.43	0.5	0.13
Netherl.	34939.45	0.99	1.42	16760.03	0.26	26.12	33.70
Poland	18524.68	0.96	3.83	37079.18	-0.21	157.72	151.99
Portugal	28380.16	0.99	2.47	10790.29	0.27	70.99	27.09
Slovak Re.	15382.81	0.94	2.31	5365.85	-0.03	12.7	17.40
Slovenia	33080.58	0.88	2.99	1972.28	0.11	10.5	8.36
Spain	28642.61	1	1.91	46445.21	0.66	155.28	113.92
Sweden	32562.58	1	1.28	9652.45	0.42	25.76	49.16
United Kgd	36745.56	1	1.99	64033.23	0.44	107.08	151.95
Sum/Aver.	33555.69	0.95	2.55	471454.19	0.21	1468.22	1468.22

Table 2: Income, population, emissions, and total deposition in 2020.

Figure 3 illustrates the results of Table 2 by scaling the numbers for 2000 down to 100, which shows that considerable differences between countries will arise both in terms of economic and population growth. In Cyprus, for example, the average economic growth from 2003 to 2020 (panel a) will be 5.05%, causing a considerable tendency to a decrease in emissions. On the other hand, Cyprus will also face the highest population growth, which annuls the decrease in emissions (panels b and c). The same type of development is foreseen in Ireland. In contrast, high economic growth in Hungary, Latvia, Lithuania, and Poland is supported by low population growth, leading to a greater than average decrease in emissions. Panel d shows, however, that the change in deposits is much more evenly distributed than that in emissions, as the situation of neighboring countries also contributes to it.

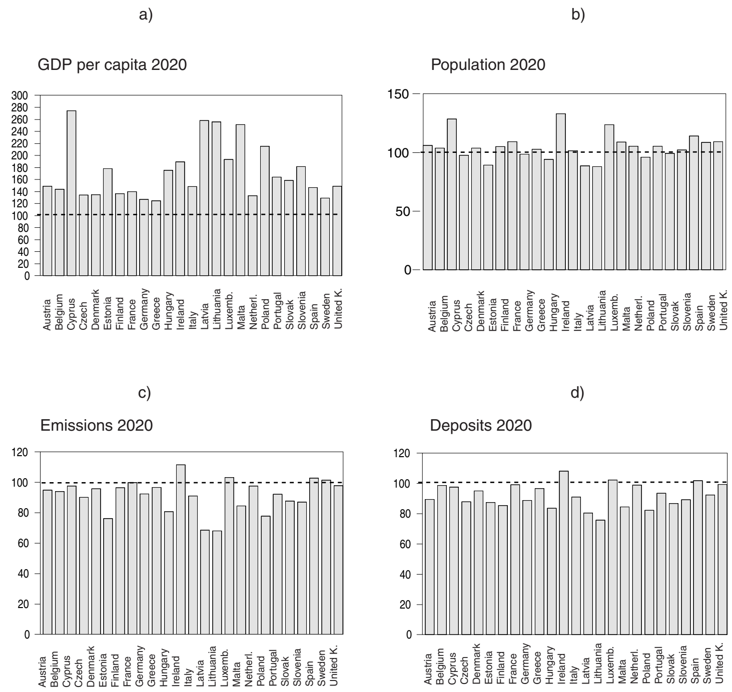

Figure 3: A comparison between the years 2000 and 2020. The values for 2000 = 100.

5 Sensitivity analysis of emissions

According to (8), the main determinants of emissions are income and population, the projections of which are provided in Table 2. This Section aims to quantify the uncertainty in these projections by providing alternative numbers. Since total deposits depend on emissions in neighboring countries, they are rather complicated to interpret. The sensitivity results are thus reported here only in terms of emissions.

The estimates of the income trends provide standard 95% confidence limits, showing that the implied average economic growth from 2003 to 2020, which in the basic case was 2.55%, becomes 1.31% in the case of the lower confidence limit and 3.79% in the higher. Given the negative elasticity of emissions in terms of incomes [Cf. (8)], one expects to see lower emissions for the higher confidence limit of $GDPpc$ and *vice versa*.

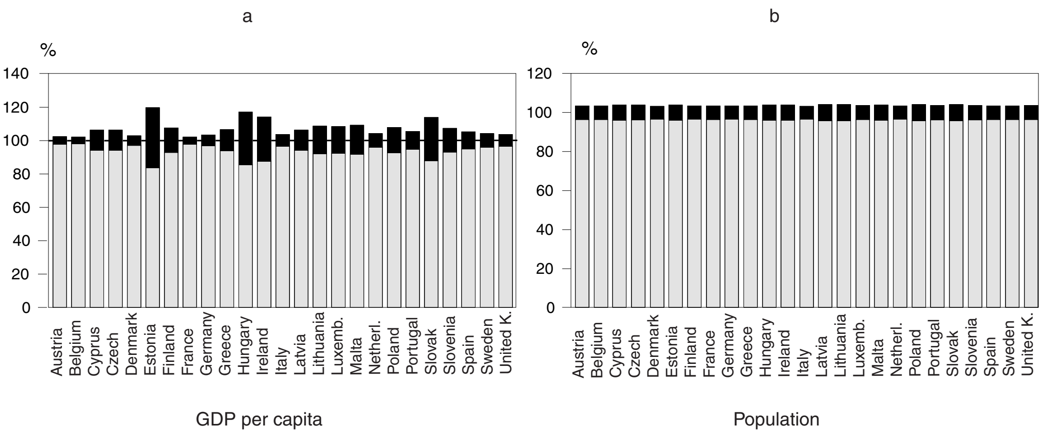

Figure 4: The confidence interval of emissions for $GDPpc$ and population in 2020.

Figure 4a shows that this is indeed the case. Normalizing the emissions in 2000 to 100, the higher confidence limit for income (grey bar) shows the emission that will be below it (94.99 on the average), whereas the lower confidence limit (grey + black bar) shows emissions above it (104.65, on average). The black bar shows the confidence interval, which in most cases is narrow, the smallest values being seen in the old *EU* members, such as Belgium, France, and Austria. New members, such as the Slovak Republic, Hungary, and Estonia exhibit largest confidence intervals, but this difference is mostly due to shorter *GDPpc* series from these countries. In contrast, relatively large confidence intervals in Finland, Ireland, and Luxembourg, indicate a genuine variation in their growth histories since data from these countries is in time series as long as from other older members.

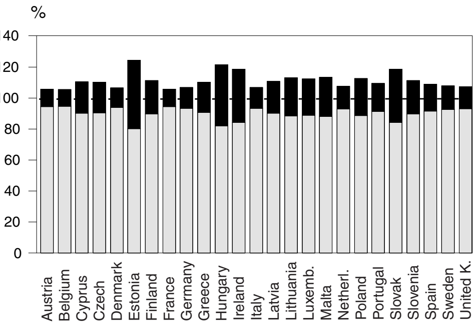

Figure 5: The worst-worst versus best-best confidence interval of emissions 2020.

The population projections in Table 2 come from The United Nations (2007), and are available in three variants, low, medium, and high. These variants mainly differ in terms of fertility behavior, but other factors, such as immigration, are also considered. The numbers in Table 2 refer to the medium variant, so that we can recalculate the emissions in 2020 for low and high variants. The medium variant projection for 2020 for the total population in EU_{25} is 471, 454 thousand people, whereas the low and high variant projections are 454, 661 and 488, 074 correspondingly, the difference between the latter two being 7.34%. The emission calculations, which are performed under the assumption that *GDPpc* proceeds as rapidly as in the benchmark projection in spite of higher population growth, show that this difference is almost directly transformed into a difference in emissions, which for the low and high variants is 1415.34 and 1520.52 with a difference of 7.43%, respectively, i.e., the demographic uncertainty generates almost as high uncertainty in emissions as the economic growth. Nevertheless, this risk is much more evenly distributed among countries [Figure 4*b*].

Figure 5 summarizes the sensitivity analysis by showing the worst-worst against the best-best alternatives, the former referring to slow economic and fast demographic growth rates and *vice versa*. On average, the spread is 20.98% of emissions in 2020. Together with the results from Figure 4. This demonstrates that while the mean projection 2020 emissions constitute 92.94% of 2000 emissions in EU_{25}, and in the best-best scenario get 2020 emissions down to 85.41%, in the worst-worst scenario 2020 emissions may rise to 101.10%. The latter number is not a significant increase in emissions on average, but much higher values are seen in Estonia (44.33%), Hungary (39.40%), Ireland (34.46%), and the Slovak Republic (34.26%) implying that in these countries the emissions increase may lead to significant effects on public health because of the dense population exposed. The reason for such an increase is a multiplicative effect from per capita GDP growth with negative elasticity and a population size with elasticity equal to one: in the worst-worst scenario the population grows rapidly increasing emissions through consumption (e.g., through the number of cars) while the per capita GDP grows slowly vanishing positive feedback between wealth and environmental concerns as the EKC hypothesis suggests.

6 Conclusions

This paper suggests that transboundary air pollution can be understood by applying the concept of gravity, which has been intensively utilized in the theory of international trade. To summarize the salient features of multilateral emission trade, we develop a gravity index that indicates how vulnerable a country is to emissions from abroad. This index is used to evaluate transboundary air pollution in Europe. The results show that even though some countries are net exporters of emissions, the heaviest net importers receive so much that their total deposits are up to twice their own emissions, implying that transboundary air pollution is a serious problem in these countries.

Since air pollution is mainly generated from economic activities such as production, consumption, and transportation, summarized in the gross national product, we estimate the association between the *GDP* and emissions by utilizing the *EKC* decomposition. It turns out that richer countries use cleaner production techniques making the elasticity of emissions in terms of income negative. However, because the elasticity of emissions in terms of population is positive, emissions may increase or decrease over time, depending upon the economic and demographic growth rates.

We thus provide country-specific estimates the values for per capita incomes and population in 2020 and calculate emissions and total deposits in 2020, indicating that total emissions in EU_{25} will decrease from 1579.79 to 1468.22 kilotons. Given that considerable differences between countries will arise both in terms of economic and population growth, the decrease in emissions varies to a great extent. The decrease in deposits, however, is much more evenly distributed because emissions trading exposes even the emission decreasing countries to emissions import from abroad. Therefore, emission decreases in individual countries will be annulled unless the emission decrease are concomitant in Europe.

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